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DEEP-OCEAN SEISMOMETER IMPLANTATION SYSTEM
Phase I Final Report

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July 1989

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1a. REPORT SECURITY CLASSIFICATION	1b. RESTRICTIVE MARKINGS
Unclassified	

2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT
	Distribution unlimited; Approved for
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	public release

4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
Flow Research Report No. 481	

6a. NAME OF PERFORMING ORGANIZATION	6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
Flow Research, Inc.		DCASMA - Seattle

6c. ADDRESS (City, State, and ZIP Code)	7b. ADDRESS (City, State, and ZIP Code)
21414 - 68th Avenue South	Bldg 5D Naval Station
Kent, WA 98032	Seattle, WA 98115-5101

8a. NAME OF FUNDING/SPONSORING ORGANIZATION Naval Ocean	8b. OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
Research & Development Activity	N68462	N00014-89-C-6003

8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS			
	PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO
Department of the Navy				
Stennis Space Center, MS 39529-5004				

11. TITLE (Include Security Classification)

DEEP-OCEAN SEISMOMETER IMPLANTATION SYSTEM (U)

12. PERSONAL AUTHOR(S)
J. J. Kolle

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 12-88 TO 6-89	July 1989	33

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	
			Seismometer, OBS, Seafloor-Penetrator, Geophone

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The overall objective of this Phase I project was to determine the feasibility of a soft landing, hydraulically powered penetrator for deploying seismometers at depths of 30 to 100 meters beneath the surface of the deep-ocean bottom. Seismometers deployed at these depths will be better coupled to the sediment and will be isolated from VLF/ULF noise signals associated with surface waves at the sediment/water interface and from current-induced noise. The primary application of the implantation system will be the deployment of seismometers with increased sensitivity to signals in the VLF/ULF band. These signals may be used in ASW activity, where ease of deployment is a primary consideration. A practical system will also be of interest to the marine seismology community.

(continued on reverse)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
Dr. Philip Valent	(601) 688-4650	

DD Form 1473, JUN 86   Previous editions are obsolete.   SECURITY CLASSIFICATION OF THIS PAGE

(Continuation of item 19. Abstract)

The two primary objectives of the Phase I work were to observe the penetration rate capability of a 130-mm-diameter prototype penetrator and to determine the size, logistics and cost of a complete deep-ocean deployment system. A prototype penetrator was fabricated and tested in clay bearing silt and sand. A Phase II proposal for a prototype seismometer deployment system, including cost estimates and deployment requirements, is being submitted. This system is designed to be a compact, self-contained package that can be deployed by ship or aircraft.

Accession For

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INTRODUCTION

The work conducted by Flow Research, Inc., in this Phase I SBIR project addresses the need for new techniques of implanting seismic detectors in deep-sea sediments. Present technology allows only for surface placement or shallow emplacement of these detectors. The Lopez Island OBS intercomparison experiment in 1981 showed that OBS package design has a significant effect on the coupling of the seismometer to the sediment and that an implanted package should provide better data than a surface package. In addition, there are a number of noise signals, particularly in the VLF/ULF frequency band (0.01 to 10 Hz), that are a problem in surface or shallow seismometer emplacements (Webb and Cox, 1984). These noise signals include:

o   Stonely waves in the sediment/water interface, 0.5 to 5 Hz.

o   Sediment instability.

o   Current-induced noise in surface packages.

Deep implantation of borehole seismometer packages provides other advantages in addition to the reduction of the near-surface noise signal. Because deeper sediments are more compact and dense, these other advantages include better coupling with the seismometer package and less attenuation of seismic signals.

Deep implantation of a sensitive system such as a seismometer package presents several challenges:

o   The system must deploy the seismometer package to a depth of 100 m.

o   The seismometer must be oriented nearly vertically.

o   Deployment must not subject the seismometer to significant impact loads

In addition to these general system requirements, it has been shown that seismometer performance will improve if the following guidelines are used in the deployment package design:

o   The seismometer package should have a density similar to the sediment in which it is emplaced and should have no large mass concentrations.

o   The seismometer should be smaller than the shortest wavelength to be measured and be symmetric about its vertical axis.

The Phase I program described here has resulted in a deployment system design that meets all of these critical criteria. The system is based on a hydraulically driven drill that is integral to the seismometer package. The Phase I work shows that such a drill is capable of penetrating to a depth of 100 m from a compact, battery-powered

landing platform and that the seismometer package is deployed in a nearly vertical orientation. The system can be small compared to the wavelengths of interest and can be made nearly acoustically transparent in the target sediment.

In this final report for the Phase I project, we begin by providing background information regarding seafloor sediments and alternative concepts for seafloor penetrators. Then, the design concept for the proposed deep-ocean seismometer implantation system (DOSIS) is presented. Next, field test results for the prototype drilling system constructed during Phase I are given and discussed in detail. Finally, the conclusions of this Phase I study are presented.

BACKGROUND

A background study was carried out in the first part of the program to evaluate the properties of deep-ocean sediment and to examine alternative deployment concepts for seismometers and geophones.

Geotechnical Properties of Seafloor Sediments

The design of the drilling system depends on the cohesion and internal friction angle of the sediment. Other considerations include the stability of the hole and the presence of manganese nodules. Most data on deep-ocean geotechnical properties are limited to the first few meters of sediment, the region easily accessible to box corers; however, some deeper data have been obtained from vane shear instruments.

Figure 1 shows a compilation of deep-ocean sediment shear strength data that includes penetrations as deep as 100 m. These data show the increase in cohesive shear strength of the sediment as it is buried and consolidated. The first meter or so has a high water content and is near the liquid limit. Most data show that the cohesive strength then increases to around 10 kPa within a meter or two and increases linearly thereafter, with maximum values at 100 m of 200 kPa or so. The maximum shear strength is found in areas with the lowest sedimentation rate corresponding to the deep ocean. While the data are limited, they represent a wide variety of depositional environments. The shear strength of the sediment should not vary greatly outside the bounds represented by these data over most of the ocean bottom.

The shear strength of sediments more than a few meters below the surface is generally considerably greater than in the surface layer, Figure 2. Surface clay sediments contain up to 80% water and tend to be very weak. As sediments are buried, this water is expelled and the strength increases. Skempton (1970) has compared the
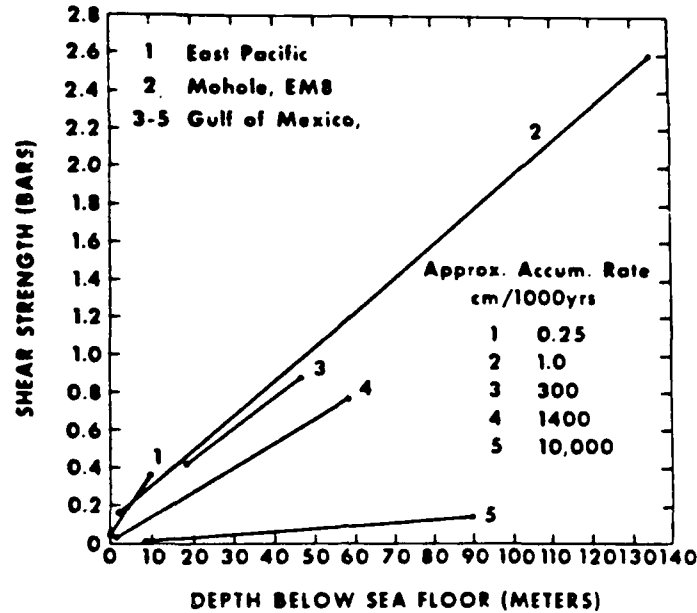
Figure 1.   Variation of shear strength with depth for areas with varying rates of sedimentation (Moore, 1964).
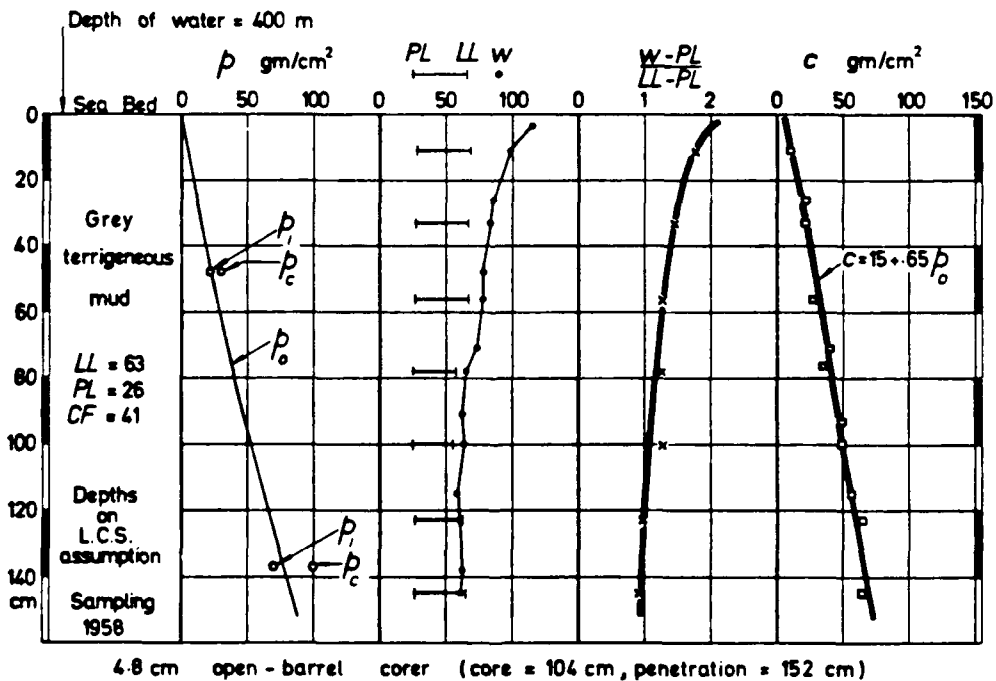

Figure 2.   Western Mediterranean sediment properties. P - consolidation pressure; PL - plastic limit; LL - liquid limit; (w-PL)/(LL-PL) - liquidity index; c - cohesive shear strength (Richards and Hamilton, 1967).

strength and water content of a variety of sediments including deep sea samples from the western Mediterranean. The cohesive strength of normally consolidated clays can be described by a Mohr's circle depiction in which the horizontal axis is the consolidation pressure, Figure 3.
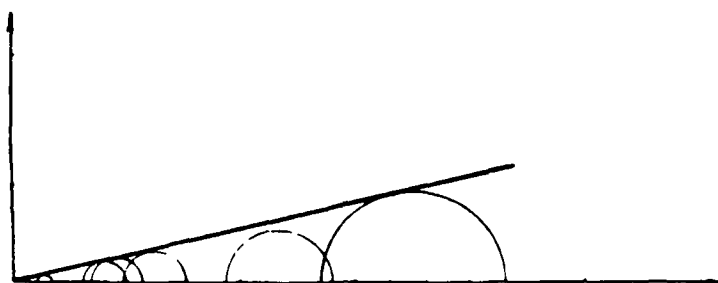
Figure 3.   Effect of consolidation pressure on shear strength of submerged clay sediments.

In weak clay sediments the unconsolidated strength is very small compared to the shear strength due to consolidation. The slope of the failure line is the angle of shearing resistance with respect to the consolidation pressure. A value of 13 degrees is typical for soft clay sediments. This should not be confused with the internal friction angle, which is essentially zero for clay sediments that are generally treated as purely cohesive soils, Figure 4.

Figure 4. Failure envelope for saturated, purely cohesive sediment.

The consolidation pressure is given by the weight of the overlying sediment. Because these sediments are in the process of consolidation, the density increases rapidly in the first few meters (Eaton, 1969). Hamilton (1974) presents several common geoacoustic models of the deep-ocean sediment in which the velocity and density do not change more than 10% in the upper 100 m. He assumes the density of unconsolidated sediment to be around 1450 kg/m^3. As a compromise between Hamilton's model for

shallow sediment and Eaton's data for deep sediments, we can assume a mean density that varies from 1450 kg/m^3 near the surface to around 1950 kg/m^3 at a depth of 100 m. The porosity in the upper sediment column probably does not drop below about 50% at the 100-m depth. The consolidation pressure at 100 m is then 931 kPa. A consolidation angle of 13 degrees then leads to an estimated cohesion of 214 kPa, which is consistent with the data given in Figure 1.

The final consideration in a deep-ocean drill is the presence of manganese nodules over large areas of the ocean floor. These are found in high concentrations only on the surface of the sediment, for example. Sorem et al. (1979) report that the manganese nodules in the eastern equatorial Pacific Ocean are typically smaller than 80 mm and lie within 50 cm of the surface. The buried nodules are reported to be friable and should not present an obstacle to drilling if the system is equipped with jets to wash the bottom before drilling commences.

Alternative Seafloor Penetrators

It has been suggested that a suitable seismometer deployment package could be deployed as a free-falling penetrator. The advantage in terms of deployment simplicity is obvious, but there are a number of problems with this approach. The kinetic energy available for penetration with such a system is limited; for example, a steel rod 10 m long and 100 mm in diameter with a mass of 615 kg will reach a terminal velocity of 12 m/s and have a kinetic energy of only 43 kJ. This may be compared with the energy required for drilling, estimated below at 78 kJ, and the energy available from a moderate-size battery pack, which can be over 1 MJ. The mass and size of a free-falling penetrator would seriously degrade the sensitivity of the seismometer.

It might be feasible to increase the penetration depth with some form of propulsion, but this would present other problems. The impact loading accompanying deceleration of a high-speed body would subject conventional seismic packages to unacceptable loads. Redesign of seismometers to withstand extreme shock loading is a nontrivial task and may not be possible with present technologies. Finally, the alignment of the package along a nearly vertical axis would be difficult to predict.

It is possible to penetrate the seafloor to the desired depths using the technology developed for the seabed cone penetrometer test (CPT) (Marr, 1981; De Ruiter, 1981; Frank, 1983), Figure 5. These devices typically consist of a massive reaction frame weighing as much as 20,000 kg and a hydraulic ram that pushes a long rod with a conical penetrometer at its tip. A vibratory component to the driving force reduces the

loads required by disrupting the sediment structure. In a sensitive clay this can reduce the shear strength by a factor of 10 or 20.

If we assume a push rod 25 mm in diameter and 50 m long, the reaction force required to penetrate 100 m into sediment with a shear strength of 10 kPa will be about 80,000 N, requiring a frame weighing at least 8000 kg. The weight of such a device and the need to handle a 100-m-long string of tubing requires a large moonpool and special handling equipment typically found only on drill ships. The cost of deploying this equipment is thus very high.

Any technique involving push rods also has the disadvantage that the string will buckle and the instrument package will deviate substantially from vertical, Figure 6. A typical secant deviation of a penetrometer at 25-m depth is 35 degrees with even greater inclination of the penetrometer head (De Ruiter, 1981). While it is possible to design self aligning seismometer housings, the diameter of such a package would be significantly larger than 10 cm and consequently more difficult to deploy.
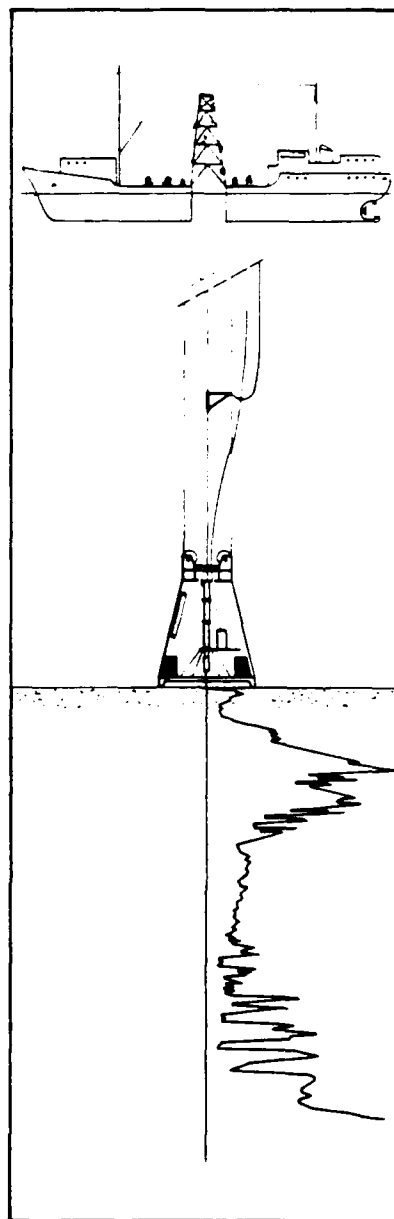

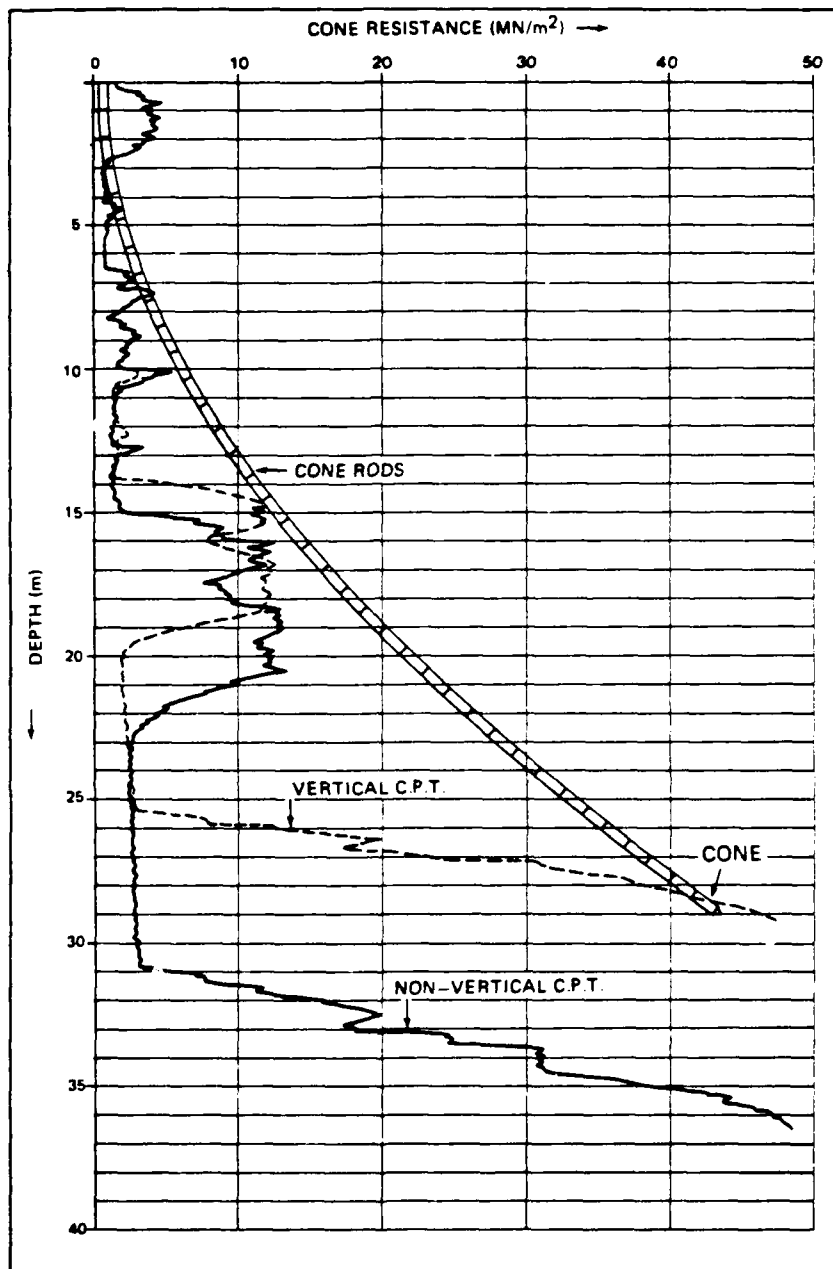Figure 5. Seafloor push rod deployment.

Figure 6. Deviation of push rod.

DEEP OCEAN SEISMOMETER IMPLANTATION SYSTEM (DOSIS)

In the Phase I research program, Flow Research has demonstrated the feasibility of a new technique for the deployment of seismometers and geophones. This system, Figure 7, is a hydraulically assisted, autonomous drilling system capable of deep, vertical deployment of conventional borehole seismometers. It consists of a surface power/pump package connected to a hydraulically powered drill. The drill is integral to the seismometer housing. The penetrator package will be driven by its own weight through the sediment.
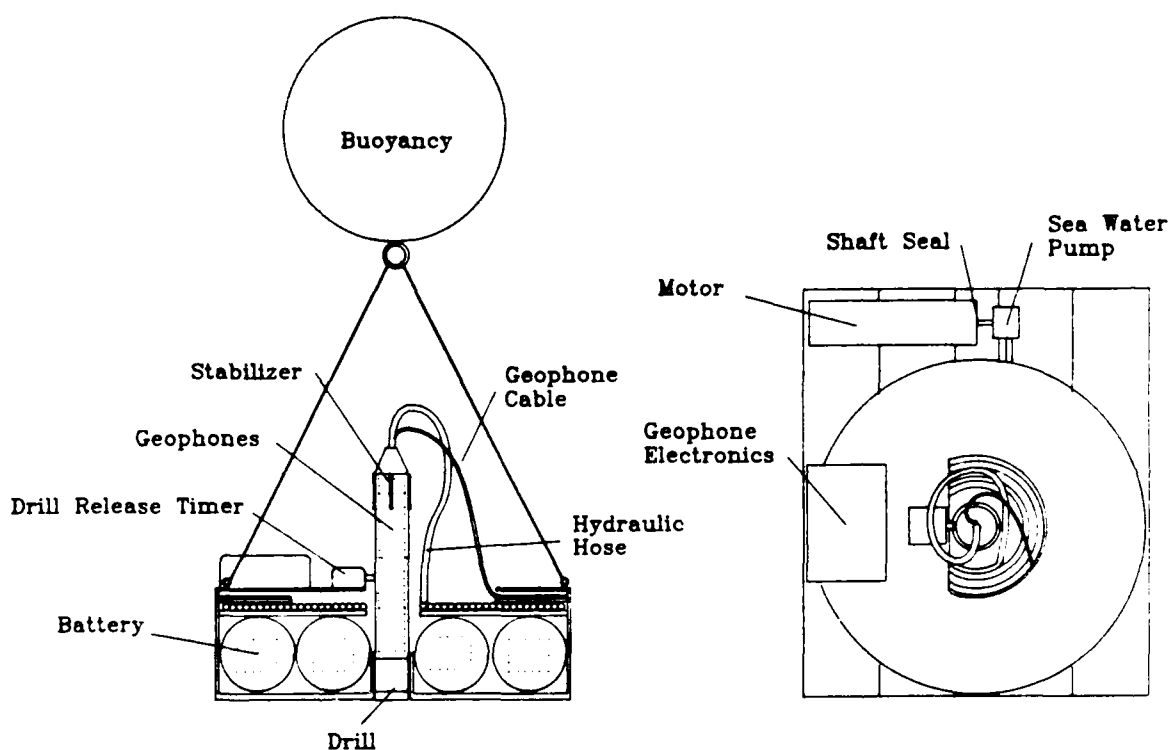
Figure 7. Deep ocean seismometer implantation system (DOSIS).

Because of the low permeability of clays, increasing the pore pressure also increases the pore volume and water content locally (Skempton, 1948). The device relies upon the observation that it is possible to locally increase the water content of a soft clay sediment the liquid limit. At this point the sediment will behave as a high-density fluid zero shear strength.

The total energy required to emplace the penetrator can be estimated from the strain energy required to shear the sediment 100%, which is approximately the strain capacity of a scft clay (Cheatham and Daniels, 1978). The total energy required is

simply the product of the shear strength and the hole volume. A 100-m-deep hole 100 mm in diameter thus requires only 78 kJ of work to drill in 100 kPa shear strength sediment. This level of energy is well within the range of a small lead/acid battery power system even allowing for large inefficiencies in conversion from electric to hydraulic energy and pressure losses.

The seafloor penetrator would be deployed from a small retrievable landing sled, Figure 8. The penetrator/seismometer package would be held in a protective housing on the trip to the bottom. The pump and lowering winch would be activated by landing or surface telemetry. Relatively high rates of penetration should be possible in soft sediments, and deployment to 100 m should not require more than an hour.
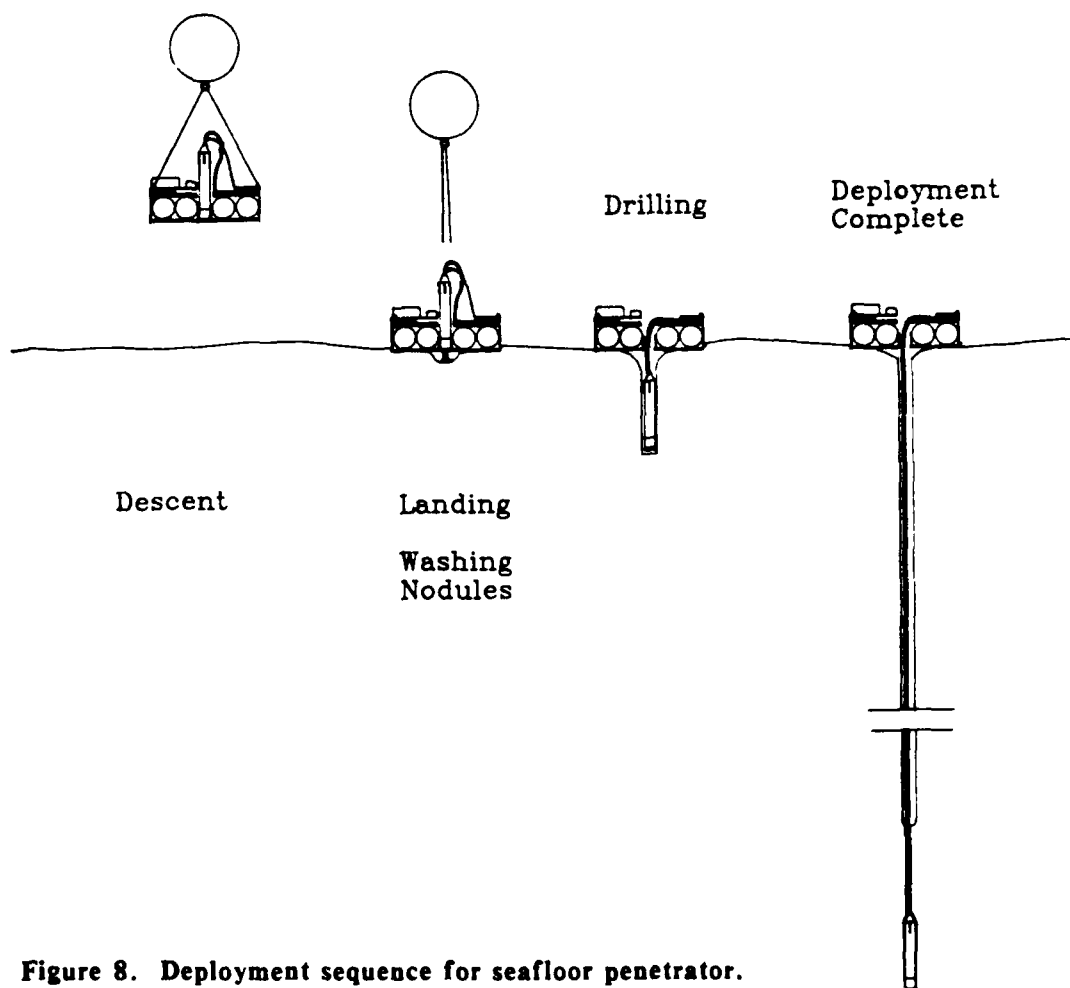

Figure 8. Deployment sequence for seafloor penetrator.

Prototype Design

The design of the prototype drilling system was driven by the assumption that the diameter of the hole should equal the outside diameter of ocean bottom seismometers currently in use including a pressure case. The dimensions of four existing seismometers are given in Table 1. These dimensions suggest that a hole diameter of 130 mm is appropriate for seismometer deployment, and this is the dimension used for Phase I testing. Miniature geophone packages, such as the Mark L-15, will require significantly smaller holes and lower power than the prototype drill.

Table 1. Seismometer dimensions.

Seismometer	Diameter (mm)	Length (mm)	Weight (kg)
Guralp CMG 3	82.5	490	---
Mark L-1-3DS	76.2	305	2.7
Mark L-4-3D	203.2	182	9.1
Mark L-15	31.8	35.6	0.14

The penetration depth is determined by the acoustic properties of the deep-ocean sediment. The required penetration has been taken from the SBIR solicitation, which calls for a minimum penetration depth of 30 m and a maximum depth of 100 m.

Drill Head Design

The proposed drilling system design is derived from the design of downhole motors used in oil and gas drilling in which the rotary power is taken from the same fluid stream used to clean the hole. The primary limitation on the motor design is the size and power available. These considerations must be balanced with the need to provide sufficient flushing water.

The DOSIS drilling system has been designed to penetrate sediments with cohesive shear strengths ranging from 10 to 100 kPa at a rate of 25 m/hr. This penetration rate requires the removal of solids at a rate of 0.1 liter/s in a 130-mm-diameter hole. The minimum flow rate required to fluidize the sediment is given by the liquid limit. A typical value for the liquid limit of oceanic clay sediments is about 150% of the dry sediment weight. The saturated sediments already contain a minimum of about

50 volume percent water. The liquid limit is reached when the sediment contains about 80% water. The minimum flow rate required to liquify the sediment at a 100-m depth is thus 0.3 liter/s (5 gpm).

Standard practice in drilling rock is to limit the solids content of the return fluid to less than 5% to ensure transport of all cuttings from the hole. This would require a flow rate of 2 liters/s (32 gpm) and would require power levels higher than those available. This low solids loading assumes, however, that the cuttings are sand sized or larger. Typically, 90% to 98% of silty clay sediments found on the ocean bottom consist of particles less than 63 microns in size (von Stackelburg, 1979). Transport of these particles can be accomplished at considerably higher solids loading, since the settling velocity of 63-micron particles is very slow. A compromise was made between maximum and minimum flow rates to ensure good hole cleaning at the field test site even if sand was encountered in the prototype system test.

A positive-displacement motor was selected to drive the drill head at 313 rpm. The motor used is a Char-Lynn A-Plus Series Gerotor with a displacement of 7.3 in^3/rev. While these motors are designed for use with hydraulic oil, they are also commonly used with water for sewer cleaning operations.

A model of drag bit drilling based on the Ernst and Merchant theory of machining was used to estimate the rate of penetration (ROP) and torque for a drill head with cutters with a rake angle of -27 degrees. This model has been shown to predict the behavior of drag bit cutters in soft shale and clay (Cheatham and Daniels, 1978). The negative rake angle is derived from experience with PDC bits, which use -20 degree rake angles. The total force on the cutter is given by

$$F = \frac{2 \, C \, A_{cs}}{1 - \sin(\beta - \alpha)}$$

where α is the rake angle, β is the friction angle of the material, C is the cohesion and A_{cs} is the cross-sectional area of the cut. The ratio of vertical to horizontal force on the cutter is

$$F_v/F_h = \tan(\beta - \alpha)$$

As the rake angle is increased, the ratio of vertical to lateral loading on the cutter increases and the tendency of the cutter to ball is reduced.

The penetration rate of the system will be proportional to the weight applied to the cutter head and inversely proportional to the sediment strength. The prototype

design will have a bit weight of around 135 N (30 lbf), which corresponds to a rate of penetration of 25 m/hr in sediment with a shear strength of 82 kPa. At this load, the torque on the bit is a constant 2.7 N-m (24 lbf-in). The motor is rated at 12 N-m (107 lbf-in) at 1400 kPa and should easily provide the required torque. Reference to Figure 1 shows that 82 kPa corresponds to a depth of about 30 m in the highest strength deep-ocean sediment. At greater depth, the ROP should slow in inverse proportion to the shear strength.

An assembly drawing of the drill is shown in Figure 9. The overall length of the assembly is 1080 mm (42.4 in). Water is provided from a 20-mm (0.75-in) hose rated at 7000 kPa (1000 psi) to drive the motor. The cutter head has six inner cutters, which are balanced to eliminate side loading of the bit as shown in Figure 10. The cutters are round to reduce bit-balling. Two flushing-water ports direct exhaust water from the motor at 0.6 liter/s (10 gpm) onto the drill face. Two gauge cutters are provided to ensure that the hole size is maintained. The cutter head provides a hole that is 3 mm larger than the main body.

At the upper end of the drill a set of four stabilizers that are 0 to 2 mm over gauge are provided. These stabilizers maintain vertical orientation of the drill and react against the walls of the hole to counteract the torque generated by the cutter head rotation.

An alternative drill design was also developed in the event that the stabilizer did not provide rotational stability. The design concept consists of a drill with two counter-rotating heads. A patent disclosure for this design has been prepared and filed with NORDA.
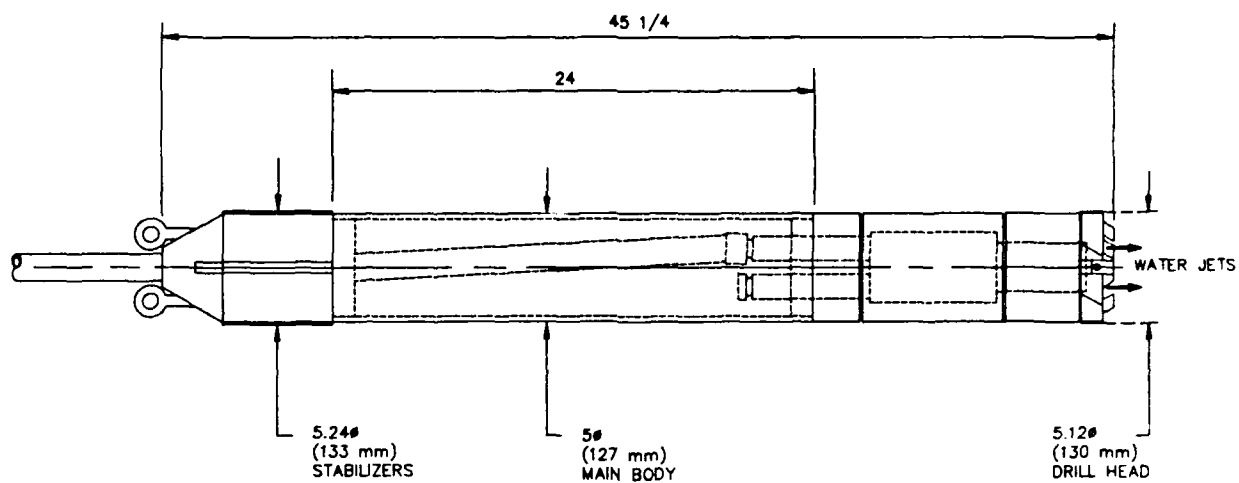
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WATER JETS

5.24⌀
(133 mm)
STABILIZERS

5⌀
(127 mm)
MAIN BODY

5.12⌀
(130 mm)
DRILL HEAD

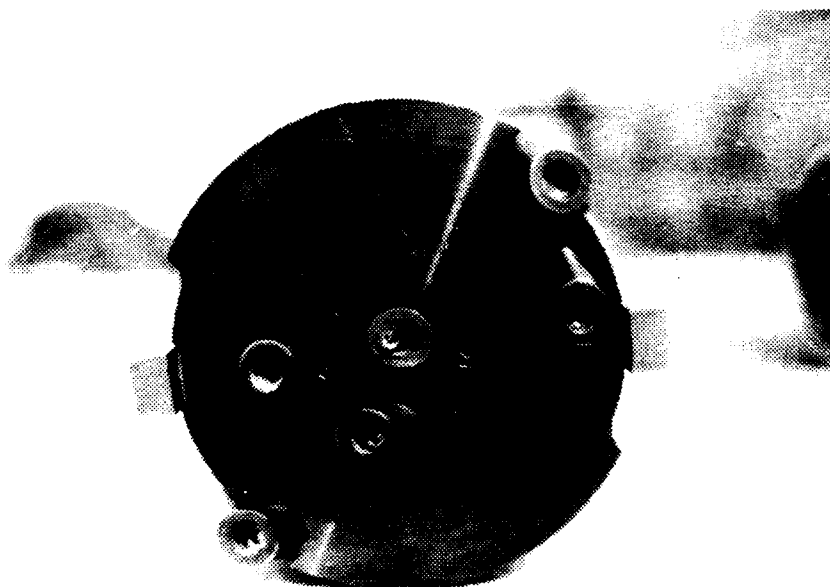Figure 9. DOSIS prototype drill assembly.

Figure 10. DOSIS drill cutter head.

FIELD TEST

The prototype DOSIS drill was tested at our site in the Kent Valley. This test site was selected on the basis of a geotechnical evaluation of the valley soil and to reduce the cost of prototype testing. The site is also equipped with a complete waste water and solids handling system.

Site Geotechnical Properties

The Washington State Department of Transportation was contacted to evaluate the test site. Our facility is located in the Kent Valley approximately 1/2 mile from State Route 167. The materials laboratory at DOT provided us with core data from two overpasses on this highway. Cores were taken to depths of 20 m at these two sites, and triaxial strength tests were carried out. The results from 21 tests are shown in Figure 11. The data show that 63% of the samples had a cohesive shear strength of 20 kPa or less and 95% are 60 kPa or less. These values bracket the estimated shear strength values for deep-sea sediments, indicating that the valley is an appropriate site for testing of the prototype drill.
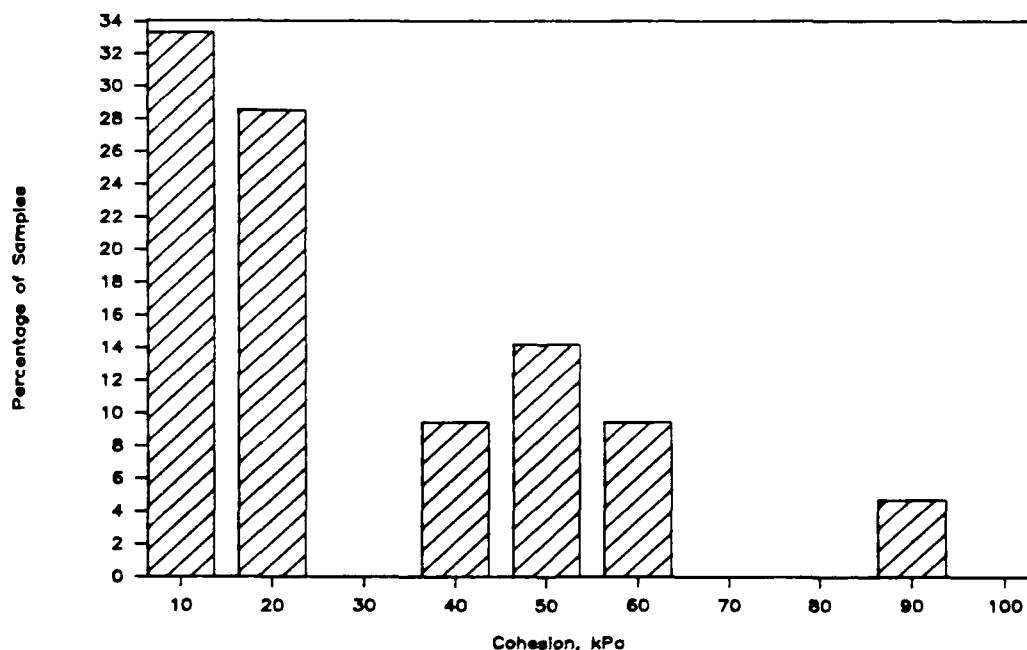

Figure 11. Histogram of Kent Valley soil shear strength.

Core descriptions show that the softest material consists of organic silt and clay within 3 m of the surface. The deeper sediment consists primarily of silt and fine sand with occasional clay, medium-coarse sand and some gravel and cobbles.

A test boring survey was carried out to determine the geotechnical properties of the test site. The contractors report is given in the Appendix. This work included collecting samples with a hollow stem auger and a Dutch cone penetrometer test. This evaluation generally confirmed the data from the DOT. The lithology and cone test results are presented in Figure 12. The section consists of sand, silt and minor clay. The Dutch cone test reveals the in situ properties of unconsolidated materials such as silt and sand. The shear strength of this material is derived mostly from the confining effect of overburden stress on the material which is otherwise merely a loose sand. The material down to a depth of 6 m has enough clay content to maintain viscosity and solids removal as well as preventing collapse of the hole.
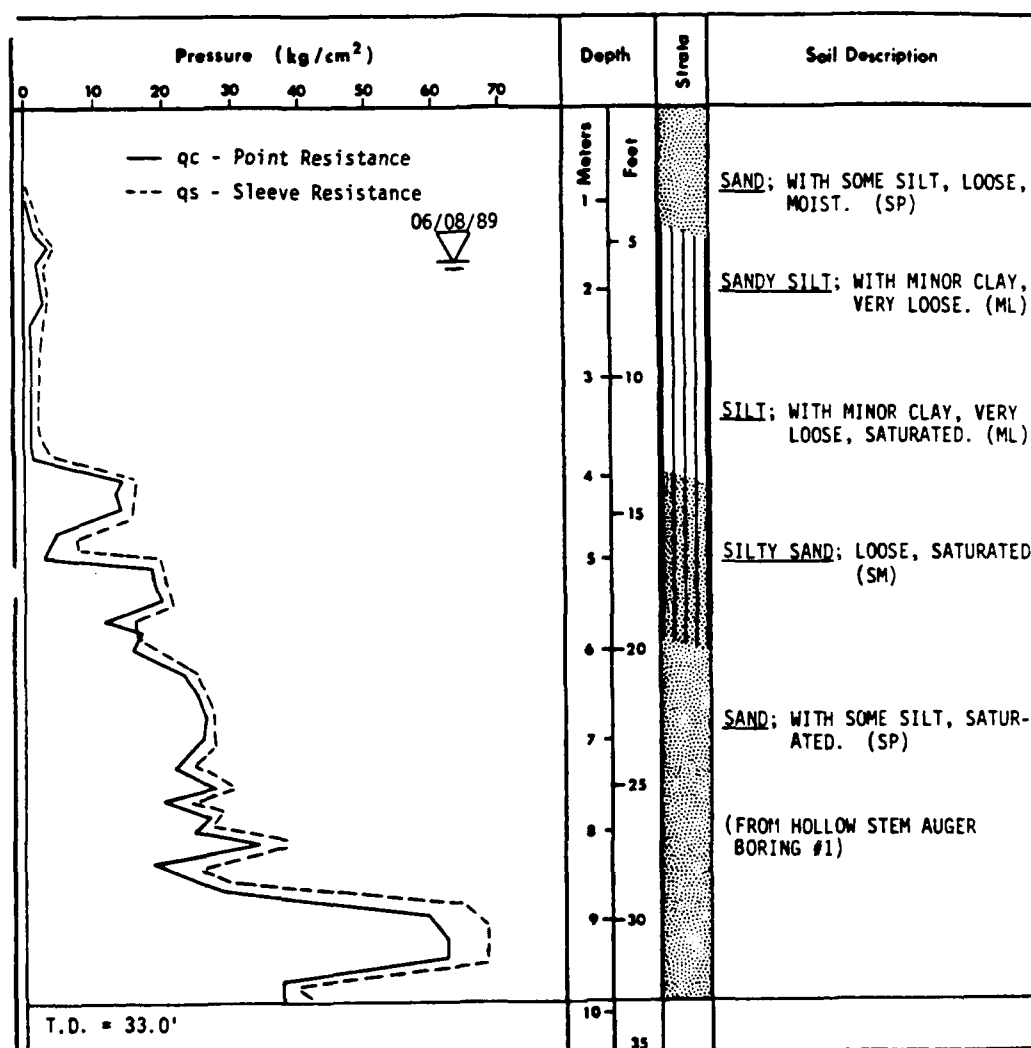

Figure 12. Core description and Dutch cone test results at test site.

Test Setup

Field testing of the drilling system was carried out at the site in the Kent Valley. The test arrangement is shown in Figure 13. Power for the drilling system was provided by a matched pair of small triplex pumps. These were connected to the drill by a 30-m length of 13-mm hose and 15 m of 20-mm hose. The hose was passed through a sheave to assist in lowering. A steel cable was also attached to the drill to control the drilling weight-on-bit (WOB) and to ensure recovery. A lowering winch with a braking system was mounted on a load frame to handle the cable.

The holes were cased with plastic tubing to a depth of 1.2 to 1.5 m. A return line from the casing was fed into a spoils tank where drilled solids were collected. Excess water was pumped into the sewer in compliance with environmental protection requirements.

Figure 13. Test setup for DOSIS showing lowering frame, casing, and spoils tank.

Rate-of-Penetration Results

A total of five holes were drilled. ROP results are given as a function of depth in Figure 14. The first hole (H1) was used to test the effect of the WOB on the ROP. A system of counterweights was installed to apply a constant tension to the lowering cable. The WOB is found by subtracting the cable tension from the submerged drill weight. This test showed that effective drilling required that the full weight of the tool, filled with sand, was required to drill at a reasonable weight.

The tool was torquing considerably during the first test, so a number of modifications were made. The swivel was operated with a clearance seal to allow a portion of the water to leak and flush the back of the tool face and prevent fouling. The leak flow rate was perceived to be too high, so the flushing ports were enlarged to allow higher flow and better cleaning of the tool face. The stabilizer mounting system was found to be inadequate to hold the stabilizers in place, so it was modified to allow larger set screws. Finally, the gauge cutters were provided with the same negative rake angle as the inner cutters to prevent excessive torquing.

The second hole (H2) was drilled with a stabilizer extension of 1.25 mm (0.050 in) into the sidewall. This drill showed good penetration, and the torquing problem was reduced but not eliminated.

The third hole (H3) was drilled with the same stabilizer configuration but with 0.66 liter/s (10.5 gpm) flow as opposed to 0.50 liter/s (8 gpm) used on the first two tests. In addition, the hose diameter was increased from 13 to 19 mm (0.5 to 0.75 in) and a sheave was provided in an attempt to prevent torsional buckling of the hose. These measures eliminated buckling of the hose, but occasional torsion was still observed. Upon recovery of the drill from a depth of 5 m (16 ft), the tool face was balled with a sticky clay. This is in an interval of low ROP, which may be caused by poor cleaning of the face. This drill test was videotaped by NORDA.

The stabilizer extension was increased to its maximum of 2 mm (0.075 in) for the fourth hole (H4). This step eliminated torsion of the hose without any reduction in ROP.

For the fifth and final drill test (H5), a seal assembly was introduced in the swivel to minimize leakage. This step approximately doubled the flow of water to the drilling face. The ROP observed with this configuration was the highest of all five tests, and torquing was not observed. Gaps in the data occur when drilling was interrupted because of loss of water around the casing and when one of the supply water pumps ran out of gas. A videotape of this test has been provided to NORDA.
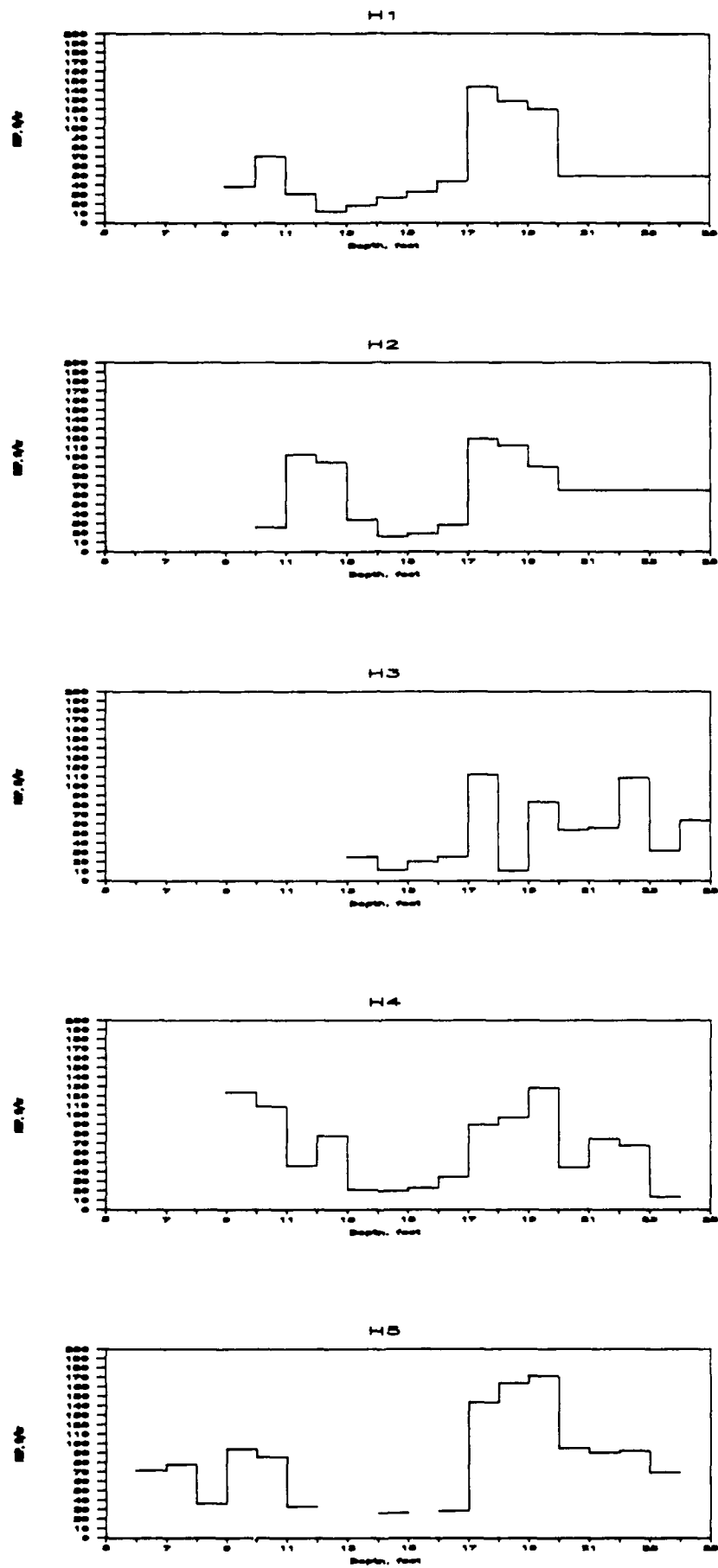
Figure 14. Rate-of-penetration results for five drilling tests.

The observed rate of penetration varies with depth and the type of soil penetrated. The average ROP is between 10 and 40 m/hr (30 and 120 ft/hr) which is close to the target of 25 m/hr. The ROP in the interval between 4 and 5 m (13 and 16 ft) may slow because of poor cleaning of the bit in layers of clay. Comparison with the Dutch cone test data shows that the shear strength also increases here to above 1500 kPa.

In all of the tests, penetration stopped at a depth of about 8 m (26 ft). The sand grain size at this depth becomes too large for effective transport by the flushing water. Samples of material from the return water show that only silt- and fine-sand-sized particles were returned. Examination of the drill cavity showed an accumulation of medium- to coarse-grained sand. When enough of this material accumulates, it may trap the tool. It is also possible that heaving of the borehole walls traps the tool at this depth. Heaving of the borehole was observed during the test boring below 5 m (16 ft).

In one instance, H2, the hole collapsed for a significant distance above the tool at the end of the test. This collapse was accompanied by a sudden drop of water level in the hole and flow of water from adjacent holes. Recovery of the tool was carried out by washing the area above the trapped drill with a high-flow nozzle for several hours while maintaining tension on the recovery line. The tool was trapped in the hole for almost 72 hours. Upon recovery, the motor did not turn because of rust accumulation; but, after cleaning, the motor appeared to operate normally and was used for the last three tests.

Hydraulic Power Requirements

The motor was tested to determine the pressure drop and power required for free operation. At a measured flow rate of 0.73 liter/s (11.6 gpm), the pressure drop across the motor was 1100 kPa (160 psi), while at 0.27 liter/s (4.3 gpm), the pressure drop was 300 kPa (43 psi). These are consistent with a power law dependence of pressure drop on flow rate through the motor with an exponent of 1.3.

The first hole was drilled with a 0.51 liter/s (8.15 gpm) flow at 1900 kPa (280 psi) total pressure drop. The pressure during drilling was essentially the same, except for occasional pressure spikes of 140 to 340 kPa (20 to 50 psi) that accompanied torsion of the drill. The hydraulic power required for drilling is much lower than power losses due to motor friction and pressure losses in the hose and manifold. The partition of pressure losses in this configuration can be calculated from the equations for turbulent pressure loss in tubes and nozzles as given on the following page.

30 m x 13 mm dia. hose:	480
Motor:	700
20 cm x 4.8 mm dia. flushing line:	330
Flushing nozzles + clearance gap (TFA=33.mm^2):	320
Drilling torque:	80
TOTAL:	1900 kPa

The third hole was drilled with 0.66 liter/s (10.5 gpm) at a pressure gauge reading of 2900 kPa (425 psi). Calibration of the gauges showed that the actual operating pressure was 2400 kPa (350 psi). The pressure losses in this configuration were:

30 m x 13 mm dia. hose:	720
15 m x 20 mm dia. hose:	50
Motor:	970
20 cm x 4.8 mm dia. flushing line:	520
Flushing nozzles + clearance gap (TFA=81 mm^2):	90
Drilling torque:	60
TOTAL:	2410 kPa

At the flow rates used, the pressure losses are greater than the pressure required to operate the motor. However, several steps can be taken to improve the efficiency of the system:

o   Eliminate 13-mm (0.5-in) diameter hose.

o   Operate at 0.44 liter/s (7 gpm) or less.

o   Increase flushing line diameter.

Under these conditions, the system can be operated at a pressure of 700 kPa (100 psi), the motor will require 375 watts (0.5 hhp) and the system should provide comparable performance in silt and clay sediments.

Vertical Deviation

The Phase I work included a demonstration of the vertical stability of the drill head. This was accomplished by a single-shot wireline drift tool, Figure 15. The tool has a pendulum and a timer that presses the tip of the pendulum into a soft aluminum target after a preset time. The drift tool was mounted in the body cavity of the DOSIS drill using the hose-clamping screw. This assembly was lowered to a depth of 4.5 m (15 ft) in the fourth hole (H4). The hole beneath this point had collapsed. Upon retrieval, the deviation was found to be less than 1 degree as seen in Figure 16. Hole deviation for this drill should be small, since the mass of the motor acts as a pendulum suspended from the stabilizers. If any deviation occurs, the drilling forces will act to right the tool.
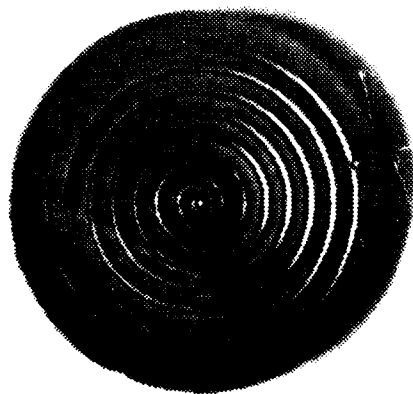
Figure 15. Wireline drift tool.

Figure 16.   Drift tool target. Maximum deviation is 7 degrees; central indentation
indicates zero drift.

DISCUSSION

The drilling tests showed the feasibility of penetrating soft sediments with a low-powered drilling system. The major problems encountered during drilling were:

o   Insufficient transport of sand-sized particles.

o   Soil heave.

o   Inadequate cutter head cleaning.

The first two of these are problems that occur in sandy noncohesive sediment. These are not serious obstacles to deep-ocean deployment, where sand-sized material is unusual. Sand-sized material may be encountered in thin (100 mm) layers of volcanic ash, which should not present a major obstacle to drilling. The drill was also entrapped by heaving, noncohesive sand. The clay sediment encountered in the deep ocean is cohesive and should not heave.

The low ROP encountered between 4 and 5 m was probably due to balling of the cutter head with clay. This interval also coincides with an increase in shear strength to as much as 1500 kPa, which is an order of magnitude greater than expected for deep-sea clay sediments. Improved cleaning of the cutter head should reduce this tendency if strong, sticky clays are encountered.

A deep borehole in weak clay sediment may be unstable if the density of fluid in the hole is too low. Instability occurs if the shear stress due to the difference between overburden stress and borehole pressure becomes greater than the shear strength. At the liquid limit, the fluid will have a density of about 1340 kg/m³. The mean density of the sediment in the first 100 m will be as much as 1700 kg/m³. The shear stress at 100 m will be around 175 kPa. This may be compared with the estimated cohesion at this depth of about 195 kPa. Under these conditions, the hole `.   `\e marginally stable. If the overburden is denser or if the strength is lower than expected, the hole could be unstable. Any significant decrease in fluid density could also lead to collapse of the hole.

These considerations point to the importance of maintaining high solids content in the return fluid. Additional stability around the tool would also be desirable. This can be achieved hydrodynamically by maintaining a small clearance between the drill body and the borehole wall. The flow of return fluid through this annulus leads to a pressure gradient, which can help maintain stability until the body of the tool has passed. Beyond this point, some instability may be acceptable. The drawback to this approach is that it requires additional weight on the bit to overcome the lift force generated by the

lift force on the drill body.

Borehole collapse is desirable once the target depth is reached, since this will provide good coupling with the borehole walls. Collapse could be induced by arresting the drill descent at the desired depth and clearing the hole of solids by continuing to pump water. Once pumping ceases, the borehole will become unstable and collapse.
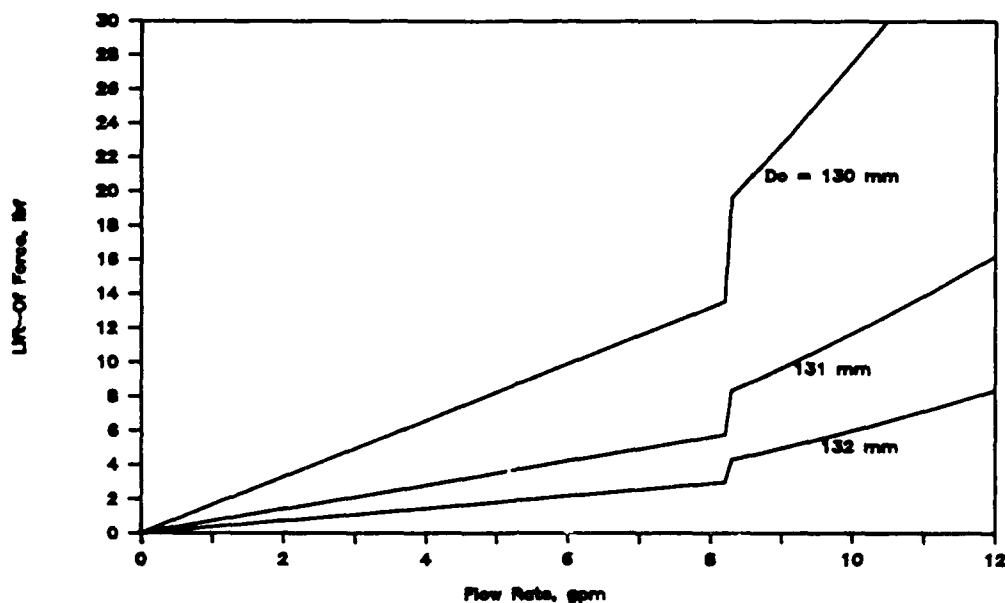

Figure 17. Hydrodynamic lift forces on drill.

CONCLUSIONS

The work carried out in the Phase I study has demonstrated the feasibility of using a hydraulically powered drilling system for the deployment of seismometers or geophones in the seafloor. A prototype 130 mm drilling system was operated at a power of 1 kW (1.33 hhp) and drilled an 8-m (25-ft) hole in clay bearing silt and sand. The penetration rate in 100 to 200 kPa sediment was over 25 m/hr (80 ft/hr). The power required to drill a 100-m-deep hole with this drill in typical deep-ocean clay sediment can be provided by small lead/acid battery system.

As a result of the Phase I work, a Phase II proposal has been prepared for the development of a seafloor system for geophone deployment. This system will be design to deploy a smaller package consistent with current NORDA deployment requirements. The 65-mm package proposed will operate at 700 kPa (100 psi) with a flow rate of only 0.075 liter/s (1.2 gpm). The power requirement for this system will be less than 100 watts for 4 hours to deploy at a depth of 100 m. The end result of this program will be a low-cost, portable deployment system for geophone packages.

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APPENDIX

SITE REPORT BY CASCADE GEOTECHNICAL

CASCADE GEOTECHNICAL
A DIVISION OF CASCADE TESTING LABORATORY, INC.
12919 N.E. 126TH PLACE   KIRKLAND, WASHINGTON 98034
KIRKLAND: (206) 821-5080   SEATTLE: (206) 525-6700

June 20, 1989
Job No. 896-2G

Flow Research
21414 68th Avenue South
Kent, Washington 98032

Attention: Jack Kolle

Reference: Test Boring and Dutch Cone Test
            Flow Research Site

Dear Mr. Kolle:

We have completed the subsurface study you requested to investi-
gate the soil conditions in the area where you tested your water
operated drilling motor. This report summarizes the subsurface
soil and ground water conditions at the location you specified.

                              SCOPE

The scope of our work included collecting and classifing subsurface
soil samples from a hollow stem auger test boring using ASTM D-1586
sampling procedures and collecting data from a Cone Penetration
Test (Dutch Cone) in accordance with the ASTM D-3441 procedure.
The data we obtained was analyzed to provide soil types and ground
water levels and to determine the undrained shear strength of the
soils.

We understand that you conducted a test of your water operated
drill motor to a depth of approximately twenty-five (25) feet. The
drill hole was uncased. The drill lost circulation and stuck at
this depth. The purpose of our study was to provide soil
parameters to be used in determining possible reasons for the water
operated drill becoming stuck and to aid in your evaluation of the
drill performance.

CASCADE GEOTECHNICAL

SUBSURFACE CONDITIONS

We observed a hollow stem auger test boring using continuous sampling that was located approximately three (3) feet north of your test location. A cone Penetration Test was done immediately after completing the soil sampling boring approximately three (3) feet northeast of your test location.

The boring and cone test were done under our direct observation. A detailed log of the soil sampling boring is shown in Appendix A. A continuous log of point and sleeve resistance for the Dutch Cone is summarized in Appendix B. Depths discussed in this report are from the surface elevation at the time of our study.

The soil sampling boring showed a loose sand to a depth of around five (5) feet. Underlying the loose sand was a very loose sandy silt to silt to a depth of twelve (12) feet. Underlying the silt was a silty sand to sand which extended to the termination depth of twenty-nine (29) feet.

Ground water was noted at six (6) feet. All the soils below this depth were saturated and loose. We noted heave in the hollow stem auger in the sandy soils below about sixteen (16) feet. Water was added to the drill stem to control the heaving soils.

The cone penetration test results are summarized in Appendix B. The pressure values would correlate directly to apparent undrained shear strength for cohesive soils such as clays or silts. It is usually considered more correct to use the values to determine an internal angle of friction when used in noncohesive, granular soils such as are encountered.

CASCADE GEOTECHNICAL

CONCLUSIONS

The soils we noted in the test boring and cone penetration test are typical alluvial deposits commonly found in the Kent Valley area. The soils are generally very fine to fine grained noncohesive granular material.

Heave was noted at depth in the test boring we observed. Heave and caving drill holes commonly occur in saturated, loose granular soils when the overburden pressure is removed in the bore hole. The soil moves into the bore hole. Water is usually added to the drill stem to provide a sufficient overburden pressure to avoid this problem.

From our discussion with you and the subsurface information we have obtained, it appears that caving or heaving soils may have occurred during your drill test. The loss of circulation and stuck drill bit may have been caused by movement of saturated granular soil around the drill within the uncased bore hole.

We understand that your drill has been designed to use in pelagic sediments, such as very fine silts and clay soils. The soil types we noted are probably not similar to pelagic type deposits. Should you wish to test in very fine silts and clays, we will be happy to target a possible test area for you. We recommend that a test boring be done prior to your test to sample the soil types to provide a more controlled testing environment.
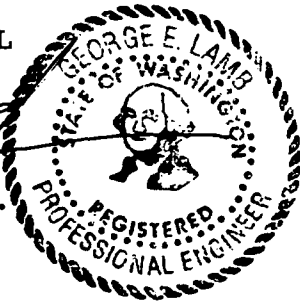
CASCADE GEOTECHNICAL

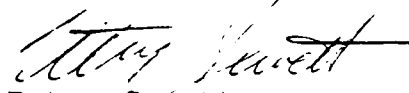June 20, 1989
Job No. 896-2G
Flow Research
Page 4

We trust that this provides sufficient information for your
needs. Should you have any additional questions or require further
testing and/or subsurface evaluation, feel free to contact us at
any time.

Sincerely,

CASCADE GEOTECHNICAL

George E. Lamb, P.E.
Principal Engineer

Peter Jewett
Engineering Geologist

PJ:lal

APPENDIX A

Project	FLOW RESEARCH	Job No. 896 - 2G	Date 06/08/89
		Boring No. 1	Dwn. By HLA
Driller	DRILLING UNLIMITED	Drill Type HOLLOW STEM AUGER	
Geo/Eng.	P. JEWETT	Hole Ø 6" I.D.	Fluid WATER @ 17'

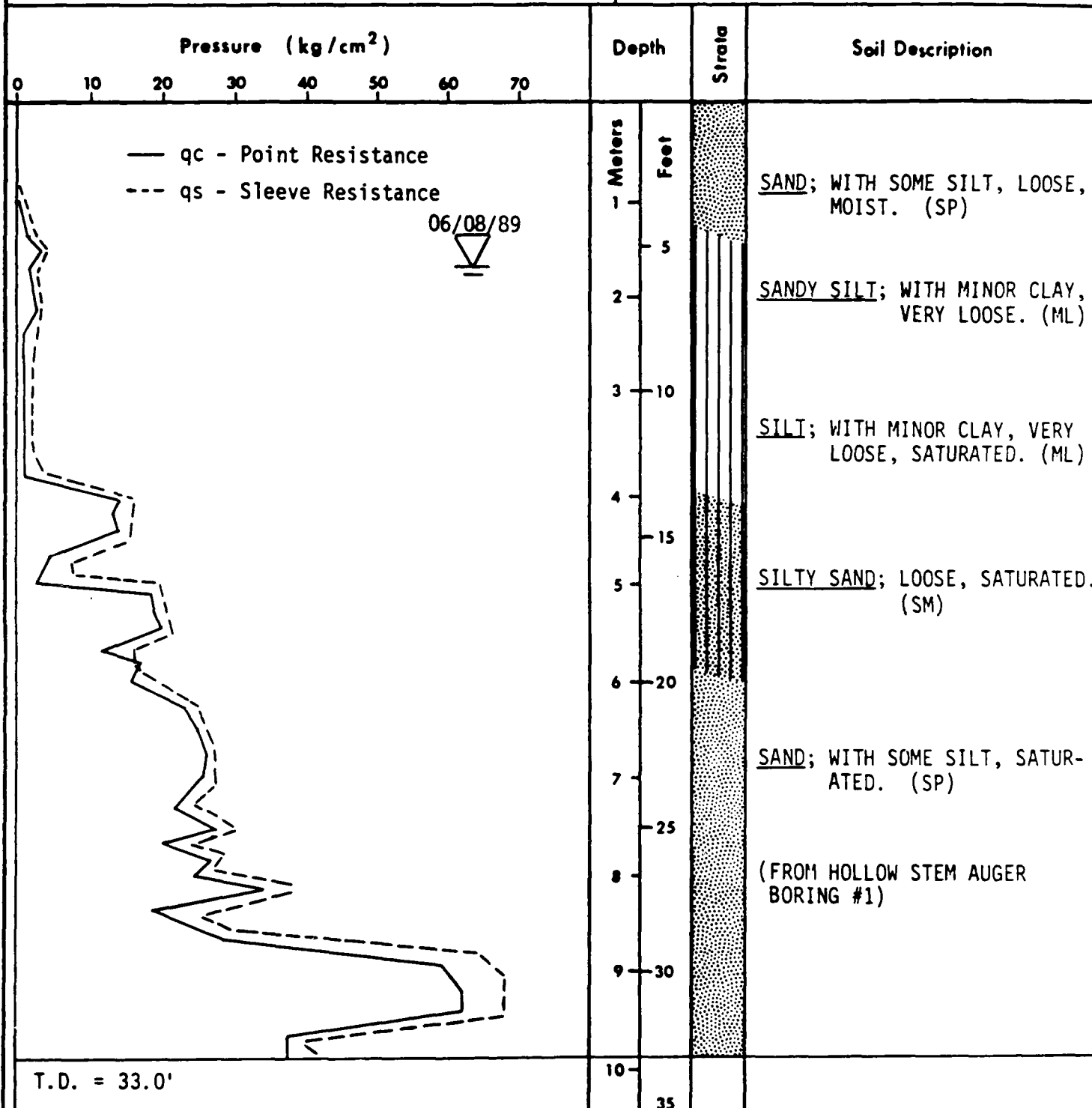| Sample Interval	Depth	Penetration Blows/6"			Blows/ft.	Strata	Soil Description & Classification	Notes
I	5	2	2	2	4		SAND; WITH SOME SILT, GRAY, LOOSE, MOIST, FINE GRAINED, WELL SORTED. (SP)	06/08/89 ▽
I		2	1	1	2		SANDY SILT; WITH MINOR CLAY, BROWN, VERY LOOSE, SATURATED. (ML)	
I	10	-	-	P	P			
I		1	1	1	2		SILT; WITH MINOR CLAY, BROWN, VERY LOOSE, SATURATED. (ML)	
I	15	2	4	5	9		SILTY SAND; BROWN, LOOSE, SATURATED, VERY FINE GRAINED. (SM)	
I		3	3	1	4			2"- 4"HEAVE ADD WATER
I	20	1	2	5	7		SILTY SAND; GRAY, SATURATED, LOOSE. (SM)	
I		4	8	13	21		SAND; WITH SOME SILT, DARK GRAY, MEDIUM DENSE, SATURATED, FINE GRAINED. (SP)	
I	25	5	10	12	22			
I	30	13	20	18	48		SAND; WITH MINOR SILT, BLACK, DENSE, MEDIUM GRAINED, SATURATED. (SP)	

T.D. = 29.0'

Notes:

TEST BORING LOG

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APPENDIX B

Project	FLOW RESEARCH	Job No.	896 - 2G	Date	06/08/89
Driller	DRILLING UNLIMITED	Boring No.	2	Dwn. By	HLA
Geo/Eng.	P. JEWETT	Drill Type	DUTCH CONE - MECHANICAL		

Pressure (kg/cm^2)

— q_c - Point Resistance
--- q_s - Sleeve Resistance

06/08/89

Depth

Strata

Soil Description

SAND; WITH SOME SILT, LOOSE, MOIST. (SP)

SANDY SILT; WITH MINOR CLAY, VERY LOOSE. (ML)

SILT; WITH MINOR CLAY, VERY LOOSE, SATURATED. (ML)

SILTY SAND; LOOSE, SATURATED. (SM)

SAND; WITH SOME SILT, SATURATED. (SP)

(FROM HOLLOW STEM AUGER BORING #1)

T.D. = 33.0'

Notes: MECHANICAL DUTCH CONE ADVANCED WITH TRUCK WEIGHT.

CASCADE GEOTECHNICAL
A DIVISION OF
CASCADE TESTING LABORATORY, INC.

STATIC PENETROMETER LOG (DUTCH CONE)

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